Distribution of icebergs in the Atlantic and Indian ocean sectors of the Antarctic region and its possible links with ENSO

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[1] The spatial distribution and multiyear variability of iceberg concentration in the Atlantic and Indian ocean sectors of the Antarctic region have been studied using ship-borne observations of iceberg occurrence. The collected dataset includes more than 40,000 reports predominantly from Russian and Australian research vessels made over the last 36 years (1970–2005). The analysis of the data has revealed a gradual decrease in the iceberg concentration away from the coast of Antarctica and a substantial variation along the coast line. Large concentration of icebergs was found in the Weddell Sea and north-east of the Antarctic Peninsula. Several regions in the Atlantic and Indian Ocean sector of Antarctica have been identified where yearly anomalies of the iceberg occurrence exhibit a noticeable correlation with El Niño/Southern Oscillation (ENSO) events. The strongest ENSO effect was observed in the region east of Drake Passage where the iceberg concentration increased by about 50% during years of the negative Southern Oscillation Index (SOI) phase. The change in the iceberg amount is explained by an increased iceberg drift into this region from the southern part of Weddell Sea and from Pacific Ocean. The latter is caused by anomalous surface pressure High and associated anti-clockwise circulation around the pressure anomaly developing in the south-eastern part of Pacific Ocean during the negative phase of ENSO. **Citation:** Romanov, Y. A., N. A. Romanova, and P. Romanov (2008), Distribution of icebergs in the Atlantic and Indian ocean sectors of the Antarctic region and its possible links with ENSO, *Geophys. Res. Lett.*, *35*, L02506, doi:10.1029/2007GL031685.

1. Introduction

[2] Icebergs present a distinctive feature of the Southern Ocean. Having calved off the margin of ice shelves, glacier tongues or ice cliffs at the coast of Antarctica, they drift both along and off the coast line while gradually melting and fracturing. Safety of navigation as well as the icebergs' effect on the thermohaline structure and on the heat and fresh water balance of the ocean, stimulate studies of iceberg movement and distribution. Ocean currents, sea ice and, to a lesser extent, winds determine the iceberg drift, thus information on the iceberg distribution and concentration can help better understand the ocean and atmospheric circulation in the polar region [*Radikevich and Romanov*, 1995].

[3] During the last three decades satellite observations have been actively used for monitoring of very large Antarctic icebergs. At the National Ice Center (NIC) of National Atmospheric and Oceanic Administration (NOAA) satellite imagery is applied to routinely track icebergs with a size of 10 nautical miles (n mi) and over (see http://www.natice.noaa.gov/products/iceberg/). A similar satellite-based approach to locate and track large Antarctic iceberg has been implemented at Brigham Young University [*Ballantyne*, 2002]. Smaller icebergs comprise more than 90% of all icebergs [*Orheim*, 1980], however they are missing in these studies because of inadequate spatial resolution of satellite data. *Schodlok et al.* [2006] tagged and monitored individual icebergs to determine prevalent iceberg tracks in Weddell Sea. Attempt to establish general patterns of iceberg drifting tracks in Antarctica has been made by *Gladstone et al.* [2001] through model simulation of iceberg formation and their subsequent drift and decay. Neither of these two latter approaches was able to provide information on the iceberg distribution, concentration and long-term variability.

[4] Manual and radar observations from ships present the primary source of information on the distribution of smaller icebergs [e.g., *Romanov*, 1996]. The difficulty in using these data consists in the fact that no standard method of observation and report format have been adopted, the data collection is not centralized, and a large number of reports are still available only as paper records. As a result earlier studies of iceberg occurrence in Antarctica were based only on limited datasets.

[5] In the last several years we have made an effort to establish the most comprehensive dataset of ship-borne observations of icebergs in Antarctica. This work concentrated primarily on digitizing and quality control of observation records from ship ice logbooks stored at the Arctic and Antarctic Research Institute (AARI), but also involved collection and processing of other available iceberg observation data. Earlier analysis of this dataset allowed for an improved characterization of the iceberg distribution in a number of regions of Antarctica [*Romanov and Romanova*, 2003, 2005]. In this study we have focused on the Atlantic and Indian ocean sectors of Antarctica where the statistics of available iceberg observations from ships is most extensive. Multiyear variations in the iceberg amount derived from the dataset were related to the Southern Oscillation Index (SOI) to establish their possible link to El Niño/Southern Oscillation (ENSO) events.

2. Observation Data

[6] The dataset we have used in this study includes 40186 observations of iceberg amount in the Atlantic and Indian

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ocean sectors of Antarctica (70°W–140°E and 46°S–80°S) over the period from 1970 to 2005. Most of observations (about 29000) were made from Russian research vessels and were acquired from Arctic and Antarctic Research Institute (AARI), Russia. AARI has also provided about 4000 iceberg reports from research vessels of other countries for the period from 1982 to 1987. (Iceberg observation data are the property of Arctic and Antarctic Institute (AARI) and are available upon request from Ivan E. Frolov, AARI Director, Beringa str. 38, S.-Peterburg, 199397, Russia, e-mail: frolov@aari.nw.ru.) These data were combined with a dataset of iceberg observations made from Australian ships from 1978 to 2001 (~7000 observation records). The latter is maintained by Dr. T.H. Jacka of the Antarctic Division Glaciology Program and is available at http://staff.acecrc.org.au/~jacka/IceData/html/icedata.html. Locations of iceberg observations included in the dataset are shown in Figure S1.[1] The vast majority of observations (~90%) were performed during the warm season, from November to April.

[7] Iceberg observations onboard Russian ships present an estimate of the number of icebergs within a 15 nautical miles (n mi) radius of the ship location (referred to as the iceberg concentration further on) and are recorded in the ship ice logbook. The majority, over 75%, of iceberg amount estimates were based on radar data; the results of visual iceberg counts comprising less than a quarter of the whole dataset were included only when radar data were unavailable and when visibility exceeded the 15 n mi range. Observations from ships of other countries were almost completely radar-based but iceberg amount estimates are made over different areas with a radius ranging from 6 n mi to 20 n mi. Therefore they had to be corrected to match the Russian data.

[8] The ability to detect icebergs both with the visual-count and with the radar-based technique generally decreases with the distance from the ship. As a result, both techniques tend to underestimate the true iceberg concentration. *Wadhams* [1988] has found that the success rate of radar detection remains about 100% within 8 n mi range of the ship but then drops almost linearly to 0% at about 22 n mi range. A similar decrease in the iceberg detection success rate is also inherent to visual observations. This conclusion is supported by the results of *Dowdeswell et al.* [1992], who reported only a small, up to 5%, difference between the iceberg amounts estimated with the visual-count and with the radar-based technique over an area of up to at least 12 n mi radius. We assume that the success rate of iceberg detection for visual and radar observations decreases similarly up to at least 15 n mi range and therefore consider iceberg counts of two types provided from Russian ships comparable. In order to achieve consistency between iceberg amount estimates made over different areas we have adjusted all observation data to a radius of 15 n mi. The correction was performed assuming that the iceberg distribution was uniform and that the iceberg detection success rate changed with distance as reported by *Wadhams* [1988].

[9] Iceberg observations were aggregated to 2° latitude and 5° longitude grid cells and averaged over a month-long time period. The selection of the grid cell size was a compromise between conflicting objectives of high spatial resolution of the map and a large number of observations per grid cell. Monthly data were then processed to estimate the overall average and multiyear monthly average values along with yearly and monthly anomalies of the iceberg concentration for every grid cell. Yearly anomalies were calculated by averaging monthly anomalies weighted by the number of observations in this month. The yearly statistics included observations performed from January to June of the current year and from July to December of the preceding year. The observed iceberg amount exhibits high variability both in time and space. For most grid cells the scatter in the observed iceberg concentration ranged from 100% to 120% of its yearly mean value. The spatial distribution of the standard deviation of the iceberg amount is presented in Figure S2.

3. Results

[10] The map of the multiyear average iceberg concentration derived from the collected ship-based observations reveals larger iceberg amounts in the vicinity of the Antarctic coast and their gradual decrease northward (see Figure 1). Variations in the iceberg concentration along the coastline are attributed primarily to variable calving rate, ocean currents and peculiarities of bottom topography. In particular, calving from Amery (~70°E–75°E), Shackleton (~95°E–100°E) and West (80°E–90°E) Ice Shelves and from Mertz Glacier (~140°E) and subsequent westward drift of icebergs in the coastal current are the primary processes causing an increased concentration of icebergs within 40°E–100°E and east of 135°E. Calving of icebergs off Lazarev Ice Shelf (14°E–15°E) and their northward drift may explain another maximum at about 12°E. Within 80°E–110°E the area of increased iceberg concentration extends several hundred kilometers off the coast line. This is due to a strong northward component in the ocean currents east of Kerguelen Plateau (~85°E) [*Bindoff et al.*, 2000] which causes icebergs to escape from the coastal current and drift northward. The pattern of iceberg distribution north of 60°S indicates that some icebergs drifting northward eventually get caught in the Antarctic Circumpolar Current and start traveling northeast. Movement of part of icebergs away from the coast over the Kerguelen Plateau and then east is confirmed by the iceberg drift modeling results of *Gladstone et al.* [2001]. Similar pattern of drift tracks was obtained from satellite-based iceberg drift monitoring of *Tchernia and Jeannin* [1984] and *Ballantyne* [2002].

[11] In the inner Weddell Sea largest concentrations of icebergs are observed along the coast line. The primary sources of icebergs in this area are Ronne-Filchner Ice Shelf in the southern-most part of Weddell Sea and Larsen Ice Shelf on the east coast of the Antarctic Peninsula. Outside the immediate coastal area, icebergs are distributed rather evenly and the iceberg concentration is high. This pattern of iceberg distribution corresponds well to iceberg track monitoring data of *Schodlok et al.* [2006], who found a large number of icebergs traveling north across Weddell Sea.

[12] An important feature of the iceberg amount distribution is a region of higher iceberg concentration stretching

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL031685.

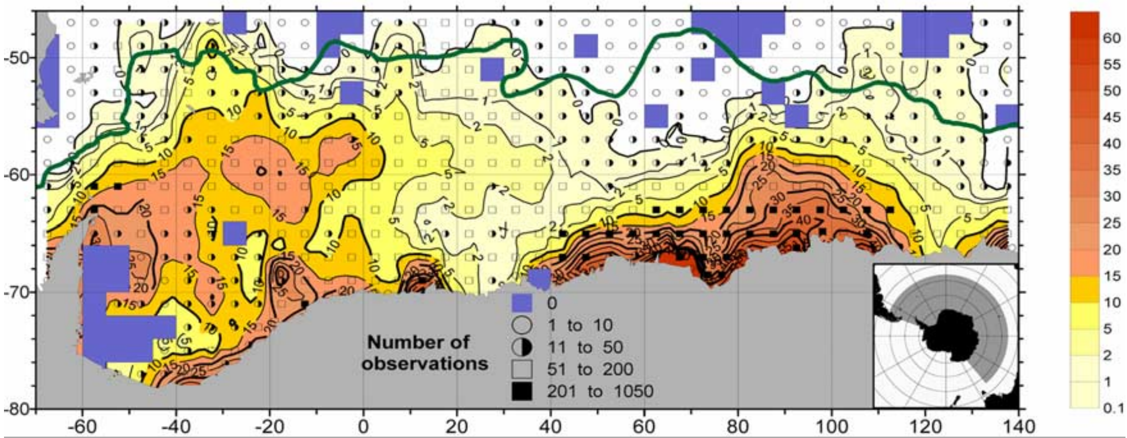

Figure 1. Average multiyear iceberg concentration (the amount of icebergs within a circle of 15 mile radius). "Zero" isoline means 0.1. Green line shows the position of Polar Front following *Orsi and Ryan* [2001]. In the insert in the bottom right the study area is shown in grey.

east and north-east off the Antarctic Peninsula to 40°E–50°E. Its southern part is formed primarily of icebergs carried out from the south-west part of Weddell Sea by the northern stream of the western part of Weddell Gyre and by icebergs drifting across the inner Weddell Sea. Icebergs transported by the Antarctic Circumpolar Current (ACC) from the Pacific Ocean through Drake Passage contribute to its northern part. The northern boundary of the area of nonzero iceberg occurrence closely follows the oceanic Polar Front. Further north icebergs are rarely seen. The collected dataset contains only three observations reporting icebergs north of 46°S, one in November 1987 at 39.9° S 49.5° W and two observations in January 1988 at 45°S, 23.7°W.

4. Effect of ENSO on Iceberg Distribution

[13] The El Niño/Southern Oscillation (ENSO) phenomenon is characterized by warming of the sea surface in the eastern equatorial part of Pacific Ocean and by weakening of the South Pacific subtropical High. It has a substantial effect on the atmospheric and oceanic circulation and brings changes to the structure of various meteorological fields including surface pressure, wind, air and sea temperature and ice concentration [*Kwok and Comiso*, 2002]. In the study of *Koshlyakov et al.* [1998] a noticeable correlation was also found between ENSO and the iceberg distribution in the South Pacific. In this paper we have used the collected dataset to see whether the effect of ENSO on the iceberg occurrence extends further on, to the Atlantic and Indian ocean sectors of Antarctica.

[14] In order to assess a possible impact of ENSO on the iceberg distribution we have examined the correlation between the yearly iceberg concentration anomalies and the Southern Oscillation Index (SOI). The SOI is defined as the difference between the standardized Tahiti and Darwin sea level pressure. Monthly SOI data were acquired from NOAA Climate Prediction Center (CPC) and were processed into yearly indices. Since the vast majority of iceberg observations were made during the warm season of the year, in this study we defined the yearly SOI index as the average of monthly SOI values for the period from November to April. Following *Kwok and Comiso* [2002] we have used SOI ≤ -1 as a criterion to identify the negative phase of SOI associated with intense ENSO episodes. Between 1970 and 2005 the warm season average SOI index remained below -1 in 1978, 1983, 1987, 1992–1993, 1998 and 2005. It should be pointed out that in 2005 the average value of SOI index below -1 was only due to anomalously low (-4.1) SOI index in February 2005, whereas indices for all other months of the warm season of 2004–2005 were only slightly positive or negative. Therefore the year of 2005 was not classified as a year of the negative phase of SOI.

[15] The map of iceberg concentration anomalies averaged over years of the negative SOI phase reveals a substantial increase in the iceberg amount in and around Drake Passage (see Figure 2). This increase amounts to about 50% of the average iceberg concentration in this region. Another positive anomaly extends from 55°E to 85°E and a strong negative anomaly is located within 5°W–15°W. We explain the positive iceberg anomaly at Drake Passage by an increased iceberg drift from the southern part of Weddell Sea as well as from Pacific Ocean through Drake Passage. The latter is the result of the anomalous surface pressure High and associated anti-clockwise circulation around the pressure anomaly which develop in the south-eastern part of Pacific Ocean during the negative phase of ENSO (see insert in Figure 2) [*Van Loon and Shea*, 1987; *Trenberth and Caron*, 2000]. A detailed analysis of processes leading to an increased iceberg drift through the Drake Passage during ENSO events is given by *Koshlyakov et al.* [1998]. A possible mechanism responsible for the negative anomaly in the iceberg concentration consists in the increase of the eastward flow through Drake Passage during the negative phase of ENSO and corresponding strengthening of the circular current in Weddell Gyre. As a result, the inflow of relatively warm Atlantic waters into the Antarctic Divergence Zone from north-east increases, and thus enhances iceberg fragmentation and decay in this region. The cause of the second positive anomaly in the iceberg concentration located at 55°E to

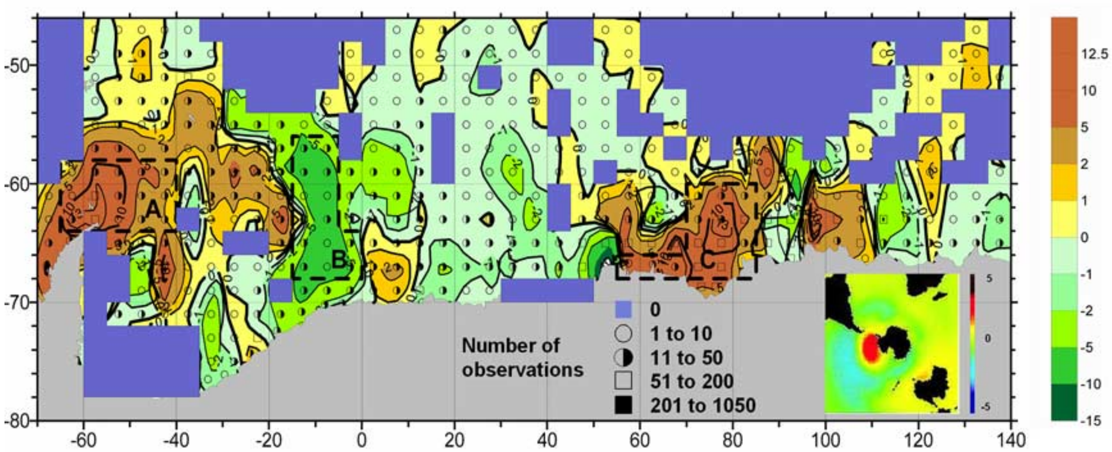

Figure 2. Anomalies of the iceberg concentration averaged over five El Niño years (1983, 1987, 1992–1993 and 1998). Three small study areas (A,B and C) used in the analysis of the year-to-year variability are shown with a dashed line (see the text of the paper). The insert in the bottom right shows the anomaly of the surface pressure (in hPa) for periods with SOI ≤ -1 from *Kwok and Comiso* [2002].

Table 1. Yearly Averaged Anomalies of Iceberg Concentration and the Number of Observations (NO) for the Western (A), Central (B) and East (C) Regions Shown in Figure 2[a]

	A		B		C		
Year	Anomalies	NO	Anomalies	NO	Anomalies	NO	SOI
1970	−8.5	28	0.5	10	−24.1	29	−0.55
1971	18.6	39	26.1	13	8.9	31	1.63
1972	-	0	-	0	**−6.3**	58	0.23
1973	−6.6	30	0.1	11	**14.1**	83	−0.77
1974	−4.2	10	-	0	-	0	2.10
1975	**−3.7**	122	−10.0	24	**10.8**	53	0.30
1976	-	0	−2.8	12	-	0	1.35
1977	−4.4	17	−1.5	6	17.3	12	−0.27
1978	−1.7	23	−14.8	12	−11.5	32	−1.38
1979	−7.3	33	−1.8	29	**−15.0**	65	−0.20
1980	**6.3**	50	**6.3**	130	**−1.7**	87	−0.58
1981	−7.8	15	–	0	**−3.4**	126	−0.62
1982	**−6.0**	212	3.3	25	**−18.4**	55	0.28
1983	**9.0**	133	**−2.6**	56	**−4.5**	130	−3.25
1984	**−3.7**	196	**0.1**	80	**−3.5**	342	−0.05
1985	**−9.3**	248	**−4.6**	55	**−9.5**	169	0.25
1986	**−5.8**	166	−2.6	22	**−9.7**	79	−0.13
1987	**19.0**	145	**−8.5**	87	**20.4**	117	−1.67
1988	**2.2**	120	13.8	42	**−0.2**	203	−0.32
1989	**4.3**	172	**−2.6**	107	**4.3**	318	1.37
1990	**0.3**	122	**3.6**	165	**3.5**	294	−0.82
1991	**−10.4**	90	−3.8	45	**−9.7**	460	−0.52
1992	**10.9**	205	**−7.2**	56	**16.5**	153	−2.05
1993	−3.2	42	−1.0	9	**−5.0**	330	−1.17
1994	−14.8	28	−8.2	9	**−7.1**	139	−0.63
1995	**−2.5**	58	1.2	33	**5.4**	257	−0.72
1996	5.0	6	−0.3	11	**5.2**	93	0.23
1997	-	0	-	0	**−0.6**	195	0.12
1998	-	0	-	0	**8.5**	183	−2.35
1999	-	0	-	0	**3.8**	195	1.27
2000	-	0	9.6	22	**−2.4**	189	1.18
2001	-	0	-	0	**−7.1**	256	0.95
2002	-	0	-	0	−1.9	11	−0.08
2003	-	0	−8.2	4	**19.4**	128	−0.83
2004	-	0	-	0	**7.8**	97	−0.23
2005	-	0	-	0	**9.9**	150	−1.17

[a]SOI is the Southern Oscillation Index averaged over November to April time period. Anomalies for years with over 50 observations are shown in bold. Correlation with SOI calculated for these years: A, −0.58 (statistically significant at the 0.05 level); B, 0.25; and C, −0.30.

85°E is less clear. At this time we can not offer a reasonable explanation of the physical mechanism involved.

[16] Only the positive anomaly at Drake Passage exhibits a significant statistical relationship with SOI. This follows from Table 1 which presents estimates of the yearly average iceberg concentration anomalies and the SOI index for 36 years, from 1970 to 2005. To reduce the noise in the time series we have averaged the iceberg concentration over small study areas centered at the maximum of each anomaly. These areas labeled "A", "B" and "C" are shown in Figure 2. When calculating correlation coefficients, only yearly data with over 50 observations of the iceberg amount were used. As it is seen from Table 1 three years of the negative SOI phase (1983, 1987 and 1992) out of five were characterized by a positive anomaly at Drake Passage (area "A" in Figure 2). In 1978 and in 1993 anomalies in this region were only slightly negative and were based on a small (less than 50) number of observations. The correlation between the iceberg concentration and SOI was equal to −0.58 and was statistically significant at 5% level. A weaker relationship with a correlation of 0.25 and −0.30 was found in the central ("B") and in the eastern ("C") study areas, respectively. In the central area ("B") negative anomalies of iceberg concentration occurred in five years of negative SOI (1978, 1983, 1987, and 1992–1993). However lower than normal iceberg amounts were also observed in years when SOI index was slightly negative or even positive. The eastern area ("C") has the longest time series of iceberg observations, extending for 36 years. In 29 years out of 36 the number of observations exceeded 50. The overall negative correlation between SOI index and iceberg concentration was mostly due to years 1987, 1992 and 1998 when the iceberg concentration was far above its average value. Maps of iceberg concentration anomalies generated individually for negative SOI phase years of 1983, 1987 and 1992 demonstrate features consistent with those seen in the combined multiyear distribution (see Figure S3).

[17] Because of the lack of observations past 1996 in the south Atlantic we could not verify whether the iceberg distribution in the Drake Passage during a strong ENSO episode of 1998 followed the pattern of earlier years of the negative SOI phase. However some implicit evidence in support of this possibility is given by *Bulgakov et al.* [2001]. This paper compares the results of ship-borne observations in 1997 and 1998 to show that the latter year was characterized by stronger currents and by more active transport of icebergs through the Drake Passage and out of south-west Weddell Sea. An increased water discharge rate through the Drake Passage in 1998 as compared to preceding years past 1992 has been also reported by *Morozov et al.* [2005].

5. Conclusion

[18] In this study iceberg observations from ships during 1970–2005 were processed to produce a map of the average iceberg distribution in the Indian and Atlantic ocean sectors of Antarctica and to study year-to-year variability of the iceberg amount. The iceberg distribution derived from these observations was generally in accord with earlier satellite-based observations of icebergs and results of the iceberg track modeling. It was found that during years of the negative SOI phase the yearly averaged amount of icebergs significantly increased east of Drake Passage. A noticeable correlation of iceberg concentration with SOI was also identified in two other areas located within 5°W–15°W and within 60°E–80°E. However in these latter cases changes in the iceberg distribution with respect to ENSO lacked consistency.

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